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ANALYSIS OF PARAMETERS OF LASER-INDUCED PERIODIC MICROSTRUCTURES (LIPSS) ON THE SURFACE OF STAINLESS STEEL USING AUTOCORRELATION FUNCTIONS

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Abstract. *In modern mechanical engineering, the control of surface quality of components, which directly affects their operational characteristics, is becoming increasingly important. One of the key aspects is the analysis of surface microstructure, particularly its periodicity, as it determines properties such as wear resistance and corrosion resistance. Laser processing is one of the promising technologies that allows the formation of regular microstructures, such as LIPSS (Laser-Induced Periodic Surface Structures). Despite extensive research, the mechanism of LIPSS formation remains not fully understood, and the results often show variable periodicity and orientation. To accurately analyze these structures, mathematical and statistical methods, such as two-dimensional autocorrelation analysis (ACF) and fast Fourier transform (FFT), are required. This study proposes a methodology for evaluating the periodicity of microstructures obtained during laser treatment of metallic samples, using digital video microscopy. The application of two-dimensional autocorrelation and spectral analysis within the Gwyddion environment ensures reproducible and objective assessment of microstructures, while demonstrating the effectiveness of ACF for surface topography analysis. The obtained data show the presence of pronounced periodicity in the studied microstructure and confirm the complexity of the LIPSS formation mechanisms, contributing to accurate quantitative analysis and adaptive control of laser modification processes.*
Keywords: *laser processing; LIPSS; autocorrelation analysis; microstructure.*

1. Introduction

Modern mechanical engineering imposes increasingly high demands on the quality of component surfaces, which directly affect their reliability, durability, and operational characteristics [1, 2]. Special attention is paid to the microstructure of the surface layer, as it determines parameters such as wear resistance, corrosion resistance, and fatigue load resistance.

One of the key aspects of microstructure analysis is the identification and quantitative assessment of its periodicity [3, 4]. Periodic structures can arise from various technological processes, such as surface plastic deformation, electroerosion processing, magnetic-abrasive processing, and laser treatment. Understanding the patterns of formation of these structures allows optimizing technological modes and improving the operational properties of products.

Surface engineering in the context of modern high-tech production is becoming increasingly important, especially in terms of precise control of material microstructure. In industries such as aerospace [5], automotive [6,7], microelectronics [8, 9] and biomedicine [10], key characteristics include not only the chemical composition and macroform of products, but also the properties of the surface layer [11], including its microtopography and texture.

One of the most promising surface modification technologies in recent years is laser processing. Thanks to its high precision, localized impact, and the ability to finely control radiation parameters, laser methods can form regular microstructures and nanostructures, such as LIPSS (Laser-Induced Periodic Surface Structures). These structures are wave-like reliefs with characteristic periods of the order of the wavelength of the radiation and smaller, arising from the interference of the incident laser beam with excited surface plasmonic fields.

However, despite extensive research, the process of LIPSS formation [12] is not fully understood, and often the result is random, with varying periodicity and orientation. As Bonse and Gräf [13] note, even slight changes in irradiation parameters—polarization, angle of incidence, pulse duration—can drastically change the resulting morphology. This creates the need to develop precise methods for quantitative analysis of the periodicity and regularity of the structures formed [14, 15].

Classical metrological methods, such as roughness measurements (R_a, R_z), are unable to adequately describe the periodic nature of LIPSS [16, 17]. To address this, mathematical-statistical approaches are increasingly being applied—such as two-dimensional autocorrelation analysis and fast Fourier transform (FFT)—to identify the dominant frequencies and directions of the relief [18 – 20]. Such methods not only provide numerical assessments but also serve as tools for visualizing periodicity, which is suitable for automated quality control.

In particular, as research by Abdelmalek et al. [21] and Magonov et al. [22] showed, the combination of Fourier analysis with high-resolution scanning microscopy (SEM, AFM) provides reliable results when controlling laser-modified surfaces. The use of available software packages, such as Gwyddion, ImageJ, and

MATLAB, allows reproducible image processing and the acquisition of objective characteristics [23].

The aim of this research is to develop and demonstrate a methodology for assessing the periodicity of microstructures obtained by laser surface treatment of metallic samples. For this, two-dimensional autocorrelation and spectral analysis of images obtained by scanning microscopy are applied, followed by processing in the Gwyddion environment. The work aims to enhance the reproducibility of the assessment and lay the groundwork for adaptive control of laser surface modification processes.

2. Applied methods

Metallic samples (material grade: AISI 304) were used in this study, having undergone laser processing to form regular microstructures. The treatment was carried out using a femtosecond laser with a wavelength of 1030 nm, a pulse duration of 300 fs, and a repetition rate of 100 kHz. The pulse energy and scanning speed were varied within a range that ensured the stable formation of LIPSS (Laser-Induced Periodic Surface Structures).

After laser processing, the samples were cleaned in an ultrasonic bath with ethanol and dried at room temperature. No additional mechanical or chemical post-treatment was applied to the surfaces in order to preserve the structure formed exclusively by laser exposure.

Method of image acquisition.

Surface morphology was investigated using a digital video microscope (HIROX KH-7700), which provides optical magnification ranging from 0.1× to 7000× and a camera resolution of 1600×1200 pixels (UXGA). These specifications ensure adequate spatial resolution for identifying surface microstructural features resulting from variations in laser processing parameters. The acquired high-resolution images, saved in TIFF and JPG formats, were subsequently utilized for numerical analysis.

Method of periodicity analysis.

Image analysis was performed using the open-source software package Gwyddion — a freely available tool for processing scanning probe microscopy data, offering functions for autocorrelation analysis, spectral transformations, filtering, and visualization.

The primary analytical method employed in this study was the two-dimensional autocorrelation function (ACF), which enables the identification of characteristic distances between repeating microstructural features, regardless of their shape or orientation. The use of ACF provides not only a quantitative assessment of periodicity but also a visual insight into the structural regularity, symmetry, and the presence of local defects.

For each image, the ACF was computed, and the dominant spatial frequency was determined from the central cross-section. The periodicity was calculated based on the position of the first maximum of the autocorrelation function. Additionally, the fast Fourier transform (FFT) was applied to confirm the results obtained via the autocorrelation method and to evaluate the orientation of structural elements.

Visualization and data processing.

The resulting autocorrelation maps and Fourier spectra were visualized using Gwyddion’s built-in tools [24], which provide accurate scale referencing and convenient image navigation. Additional statistical analysis — including the calculation of the standard deviation of periods, regularity assessment, and histogram plotting — was performed in the Python environment using the NumPy, SciPy, and Matplotlib libraries.

This approach ensured a reproducible and objective evaluation of the microstructures formed during laser treatment, and demonstrated the effectiveness of combining ACF and FFT for surface topography analysis.

3. Results and discussion

The samples of structures on the surface of AISI 304 steel obtained after laser processing (Fig. 1) demonstrate the presence of periodicity in the form of regularly spaced features aligned along specific directions, characteristic of laser-induced periodic surface structures (LIPSS).

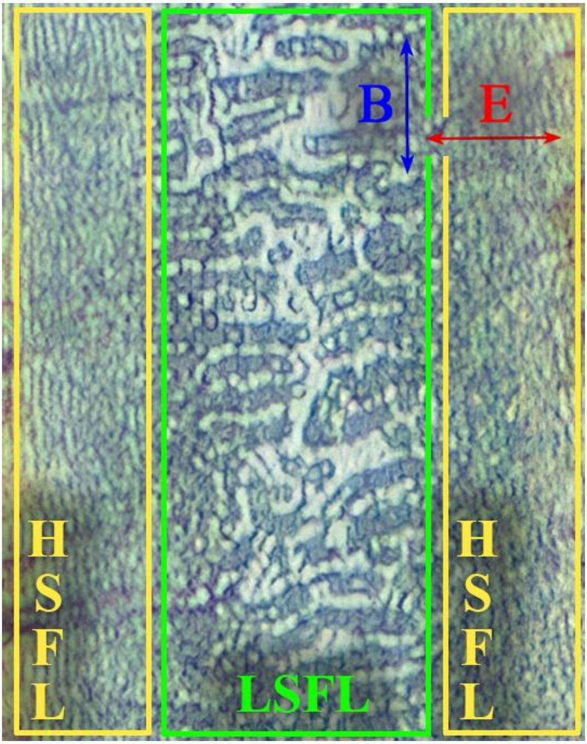


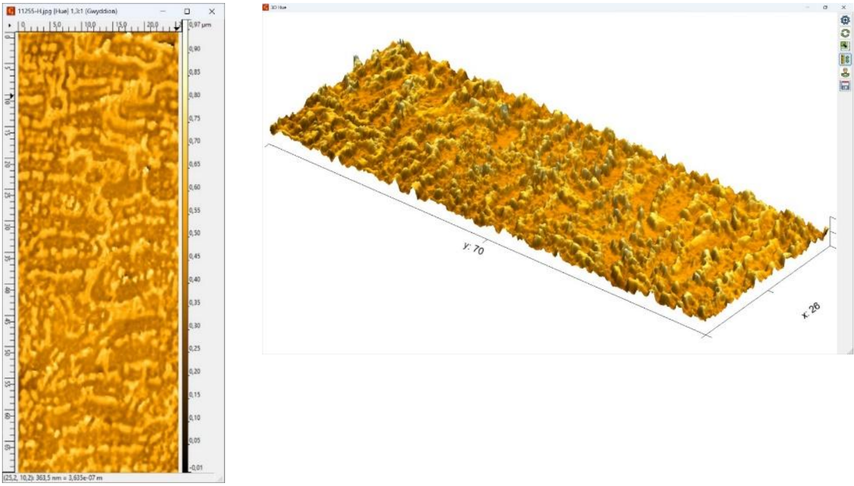
Fig. 1. Surface microstructure formed on the surface of AISI 304 steel.

The microscopy results clearly demonstrate the presence of low-spatial-frequency laser-induced periodic surface structures (LSFL) and high-spatial-frequency LIPSS (HSFL) on the sample surface (Fig. 1), as described in [25].

Autocorrelation analysis was carried out using the Gwyddion software, with preliminary selection of regions exhibiting structures of different spatial frequencies. To measure the isotropy of a surface, the autocorrelation function (1) is used:

$$R(\tau) = \int_{-\infty}^{\infty} f(x) \cdot f(x+\tau) dx, \quad (1)$$

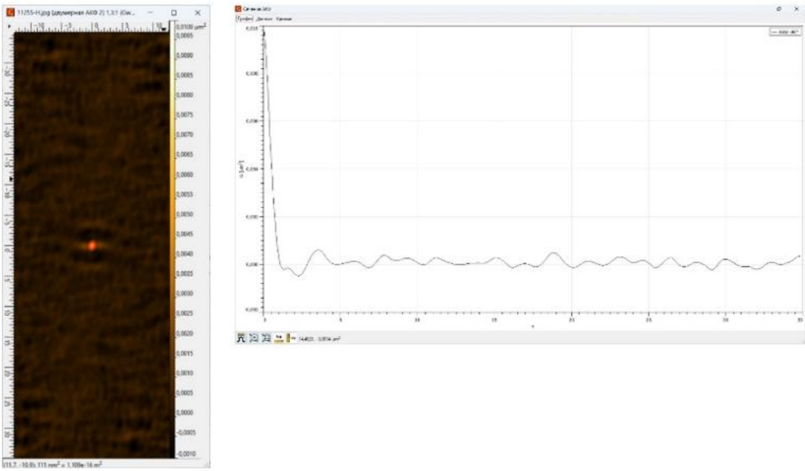
$R(\tau)$ — autocorrelation function, $f(x)$ — the function for which the autocorrelation is calculated, τ — shift (the parameter by which the function is shifted during the calculation process).



A B

Fig. 2. Analysis of the surface microstructure section with LSFL in the Gwyddion software package. A – 2D plot; B – Surface plot.

Autocorrelation analysis performed in the Gwyddion environment revealed characteristic spatial periods at the level of 3.536 µm, confirmed by regular maxima of the autocorrelation function. The measured peak parameters (height, area, width) indicate a high degree of microstructure regularity.



A B

Fig. 3. Cross-section of the autocorrelation function (ACF) (-90°) of the area with a low-frequency spatial LIPSS structure. A – 2D plot; B – Graph.

The analysis of the surface microstructure area with HSFL was carried out in a similar manner.

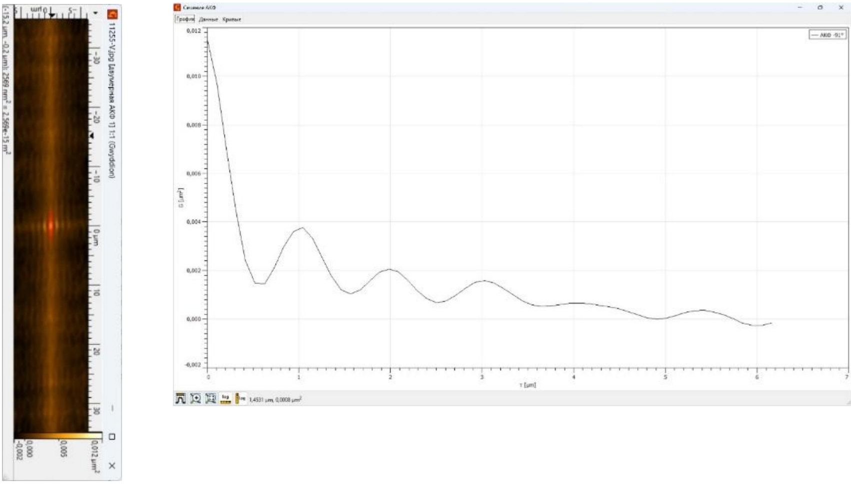
A B

Fig. 4. Analysis of the surface microstructure section with HSFL in the Gwyddion software package. A – 2D plot; B – Surface plot.

Autocorrelation analysis of the region with high-spatial-frequency LIPSS (HSFL) revealed characteristic spatial periods at the level of 1.0186 µm, confirmed by regular maxima in the autocorrelation function. The measured peak parameters (height, area, width) also indicate a high degree of microstructure regularity.

For a more in-depth analysis of the regularity of the spatial structures, a Fast Fourier Transform (FFT) of the autocorrelation function (ACF) was performed. Although the identification of a principal spatial period was expected, the spectral distribution predominantly exhibited a central peak with only minor side deviations—this may be attributed to measurement noise, low structural regularity, or fluctuations in the amplitude profile.

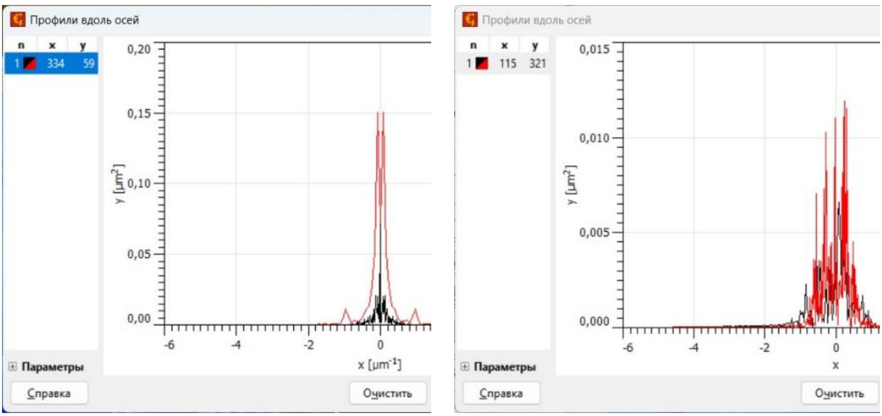
Nevertheless, the presence of side 'shoulders' near the 1 μm^{-1} coordinate confirms the existence of a dominant spatial frequency. This indicates partial structural regularity and may reflect a characteristic scale of repeating elements.



A B

Fig 5. Cross-section of the autocorrelation function (ACF) (-90°) of the area with a high-frequency spatial LIPSS structure. A – 2D plot; B – Graph.

Such a spectral pattern is typical for surfaces modified by laser irradiation in the LIPSS regime, where the formation of periodic features results from the interplay of both interference and thermal processes, often superimposed on one another.



A B

Fig. 6. FFT spectra of the autocorrelation function (ACF). A – LSFL; B – HSFL.

Thus, in this case, the FFT spectrum of the ACF serves rather as a supplementary diagnostic tool to confirm the presence of periodic components, rather than a primary method of quantitative analysis. Visual inspection of the ACF and identification of the first-order maxima remains the preferred approach in terms of accuracy and interpretability of the results.

4. Conclusions

Analysis of the autocorrelation functions (ACFs) derived from microscopic images of the processed surfaces revealed a pronounced spatial periodicity. Figure 4 presents an example of an ACF along the -90° direction, generated in Gwyddion based on the original topographic data.

The first local maximum is observed at **τ** ≈ 3.54 µm, corresponding to the characteristic period of the regular structure. Additional maxima appear at intervals of approximately 7–8 µm, indicating repeatability of the pattern within the analyzed area.

To quantitatively describe the structural regularity, local maxima on the ACF plot were marked (see Fig. 5). The coordinates of the first five maxima are listed in Table 1.

№	**τ**, µm	**h**	**A**	**w**
1	3,54	835,7	998,2	0,425
2	11,21	289,6	307,8	0,427
3	18,80	608,6	689,9	0,429
4	26,40	396,7	347,1	0,323
5	29,99	442,9	592,1	0,613

Table 1. Coordinates of the ACF maxima and repeatability parameters of the surface icrostructure section with LSFL.

Despite partial irregularity in the amplitude characteristics (**h**, **A**), where the heights (**h**) and areas (**A**) of the ACF peaks provide an estimate of the structural contrast and repeatability, the spatial positioning of the maxima exhibits satisfactory equidistance, confirming the presence of a stable periodic structure. The variation in τ values between adjacent maxima does not exceed 0.6–0.8 µm.

In addition to the primary periodic structure with a characteristic pitch of approximately 3.5 µm, high-frequency formations oriented perpendicularly to the primary ones were detected in certain surface areas (Fig. 1). These features are identifiable both in the topographic data and in the corresponding ACF cross-sections.

Figure 6 shows the annotation of additional maxima corresponding to the secondary (high-frequency) pattern. Table 2 provides their numerical characteristics.

№	τ, μm	h	A	w
1	1,02	2510,9	1 198 600	177,3
2	1,99	1194,3	586 048	180,4
3	3,01	970,2	538 348	206,7
4	4,05	389,5	336 519	263,4
5	5,38	482,5	273 321	200,7

Table 2. Coordinates of the ACF maxima and repeatability parameters of the surface microstructure section with HSFL.

As can be seen from the presented data, this structure has a smaller period (on the order of 1–2 μm), a higher frequency, and a relatively higher amplitude of autocorrelation function (ACF) oscillations in the initial interval. The width of the ACF peak (parameter **w**) can be interpreted as an indicator of the variability or dispersion in the structural periodicity. This parameter (**w**) varies from 177 to 263 nm.

Such a two-level periodicity may indicate the superposition of different mechanisms of structure formation during laser processing: the primary one is of an interference nature, while the secondary one is caused by modulations of the local thermal gradient or inhomogeneities in the energy distribution of the laser beam.

The obtained data is consistent with the formation characteristics of LIPSS structures during laser processing, where periods on the order of 1–5 μm are typically formed, depending on the wavelength and irradiation parameters. Since the mechanism of LIPSS generation remains complex and includes interference, capillary, and thermoelastic components, additional quantitative processing of the ACF helps to improve the reliability of the analysis of the resulting structure.

Such spatial decomposition of periodicities within a single processed area can serve as additional confirmation of the complexity and multi-component nature of the laser impact mechanisms. The presented data allows for the identification of the parameters of both structures with high accuracy, with the autocorrelation function serving as the primary tool for quantitative analysis, ensuring the objective identification of periods without prior assumptions about the shape or direction of the modules.

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Емілія Саприкіна, Сергій Добротворський, Борис Алексенко, Дмитро Трубін, Харків, Україна, Денис Москаль, Іржі Мартан, Плзень, Чехія

АНАЛІЗ ПАРАМЕТРІВ ЛАЗЕРНО-ІНДУКОВАНИХ ПЕРІОДИЧНИХ МІКРОСТРУКТУР (LIPSS) НА ПОВЕРХНІ НЕРЖАВІЮЧОЇ СТАЛІ З ВИКОРИСТАННЯМ АВТОКОРЕЛЯЦІЙНИХ ФУНКЦІЙ

Анотація. *У сучасному машинобудуванні дедалі більшого значення набуває контроль якості поверхні компонентів, що безпосередньо впливає на їхні експлуатаційні характеристики. Одним з ключових аспектів контролю якості є аналіз мікроструктури поверхні, зокрема такої її трибологічної характеристики як періодичность, оскільки це визначає такі властивості, як зносостійкість, оптичні властивості та корозійна стійкість. Лазерна обробка є однією з перспективних технологій, що дозволяє формувати регулярні мікроструктури, такі як LIPSS (лазерно-індуковані періодичні поверхневі структури). Незважаючи на чисельні дослідження, механізм утворення LIPSS залишається вивченим не до кінця, і результати часто демонструють змінну періодичність та орієнтацію отриманих в процесі дослідження мікроструктур. Для точного аналізу цих структур необхідні математичні та статистичні методи, такі як двовимірний автокореляційний аналіз (ACF) та швидке перетворення Фур'є (FFT). У представленому дослідженні пропонується методологія оцінки періодичності мікроструктур, які були отримано під час лазерної обробки металевих зразків. Структури було вивчено за допомогою цифрової відеомікроскопії, після чого був проведений аналіз отриманих зображень поверхні з використанням програмного середовища Gwyddion. Застосування двовимірної автокореляції та спектрального аналізу в середовищі Gwyddion забезпечує відтворювану та об'єктивну оцінку мікроструктур, одночасно демонструючи ефективність ACF для аналізу* *топографії поверхні. Для більш глибокого аналізу регулярності просторових структур було виконано швидке перетворення Фур'є (ШПФ) отриманої автокореляційної функції (АКФ). Спостереження наявності незначних додаткових бічних піків на графіку (ШПФ) поблизу координати головного піку підтверджує існування домінуючої просторової частоти. Це вказує на часткову структурну регулярність і може відображати характерний масштаб повторюваних елементів. Отримані за допомогою автокореляційного аналізу (ACF) дані показують наявність вираженої періодичності в досліджуваній мікроструктурі, одночасно підтверджуючи складність механізмів формування LIPSS, сприятимуть точному кількісному аналізу та адаптивному керуванню процесами лазерної модифікації.*

Ключові слова: *лазерна обробка; LIPSS; автокореляційний аналіз; мікроструктура.*